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EXPERIMENTAL STUDY OF CRITICAL SYSTEMS WITH Li^7H and $Zr\ H_{1.6}$ MODERATORS.

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Recently special attention has been attracted to the use of hydrides of metals as hydrogenous moderators. Hydrides of metals, containing a great amount of hydrogen per volume unit, have a strong moderating power close to that of water.

In this paper the moderating power of lithium and zirconium hydrides is considered.

Since the natural mixture of lithium isotopes has a large capture cross section (σ_c^{th} = 71), the isotope Li^7 comprising 92.5% of the natural isotope mixture is of particular interest, the thermal neutron capture cross section of Li^7 being 33 mb.

The separation of the lithium isotopes presents no difficulty, due to the large relative difference of atomic weights (17%). When insignificant admixture of Li^7 are present in lithium hydrides, or when small amounts of hafmium are found in zirconium hydride, both moderators have a sufficiently small capture cross section. Besides the zirconium reduces the neutron moderation length due to inelastic scattering (Table I).

Table I.

Moderating Properties of Li^7 Hydride, Zr Hydride and Water.

Moderator	Formula	Density (g/cm^3)	Macroscopic thermal neutron absorption cross section	Moderating Power (epithermal neutrons)
Li^7 hydride	Li^7H	0.8	0.0231	1.16
Zr hydride	$Zr\ H_{1.6}$ *)	5.0	0.0458	0.99
Water	H_2O	1.0	0.0222	1.28

*) The formula corresponds to the zirconium hydride composition, used in the critical assemblies, described later on.

T a b l e II.

Core and Reflector Composition of the PF-4 assemblies.

Element	Thickness	Canning	Notes
UO_2 (90% enrichment)	0.48 g/cm^2	Steel; 0.2 mm	In assemblies with $ZrH_{1.6}$
U_3O_8 (90% enrichment) CF_4 (75% by weight)	17 mg/cm^2	CF_4 0.1 mm	In assemblies with Li^7H
Li^7H	5 mm	Al 0.1mm	
$ZrH_{1.6}$	6 mm	None	
Be	Varied	None	Reflector
Stainless steel	"	None	Reflector

CRITICAL ASSEMBLIES WITH HYDRIDE MODERATORS.

Lithium^7 hydride and zirconium hydride have been investigated as moderators on the PF-4 physical assembly (zero-power reactor).

The detailed description of this assembly is to be found in [1], therefore here only its main characteristics are mentioned briefly.

Our physical assemblies are a set of aluminium tubes (50mm - o.d., 1mm - wall thickness, 51mm - lattice spacing) placed into a cylindrical containing vessel and surrounded by a biological shielding of cast iron blocks filled with paraffin . The core and reflector components are placed inside the aluminium tubes.

In the experiments described elements with a 47mm diameter are used (see Table II). Thin aluminium rings are inserted between the main components of the core. These rings allow to make up assemblies with various parts of volume occupied by air.

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1.1. Critical Assemblies with a Lithium Hydride Moderator.

Lithium hydride is used in assemblies with a soft energy neutron spectrum. In this hydride the ratio of hydrogen nuclei (as components of the hydride) to the nuclei of U^{235} equals from 120 to 400.

All the assemblies with lithium hydride moderators have beryllium reflectors. The thickness of the bottom and top reflector is 100 mm, whereas the side reflector is 88,3 mm thick.

The parts of volume of the reflector occupied by beryllium and aluminium are 0.82*) and 0.07 respectively. To decrease the neutron scattering effect from the wall and equipment there is a 1 mm cadmium filter around the reflector.

Five critical systems with lithium hydride moderators have been assembled. They all differed in their nuclear concentration ratios of hydrogen to uranium-235 and in the parts of volume occupied by the core components.

The determination of critical parameters of the assemblies was accomplished by means of the reciprocal counting method. Particular consideration was given to the fact that the core geometry should be possibly closer to a circular one.

Following the experimental determination of the critical number of fuel stacks several correction have been introduced.

1). The first correction for distortion of the reactor lattice or the reflector by control channels was found experimentally by measuring the effect of substituting a standard fuel stack for a control channel. Some of the systems have been assembled "pure", i.e. without the above-mentioned distortions. Check-up after introduction of this correction showed good agreement.

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*) The density of beryllium is 1.8 g/cm^3.

2). The second correction is concerned with the self-shielding effect due to some inhomogeneity in the arrangement of the uranium and moderator elements. It is to be noted that the extent of inhomogeneity varied for different assemblies.

The shielding factor was calculated according to the formula given in [2]:

$$f = \frac{\mathcal{J}(\alpha,\beta)}{\alpha\left(1 - \frac{\mathcal{J}(\alpha,\beta)}{\beta}\right)} \qquad \mathcal{J}(\alpha,\beta) = \int_1^\infty \frac{(1-e^{-\alpha t})(1-e^{-\beta t})}{1-e^{-(\alpha+\beta)t}} \cdot \frac{dt}{t^3}$$

T a b l e III.

Composition of Assemblies with Lithium-Hydride Moderators.

Assembly index.	Nuclear density $\times 10^{-20}$ 1/cm^3				
	Li^7H	U^{235}	C *)	F	Al
HL-1	208	2.04	39	156	79
HL-2	217	1.09	21	84	150
HL-3	261	1.32	25	100	86
HL-4	261	0.62	12	48	164
HL-5	347	0.79	15	60	60

*) As components of the teflon diluent and canning of the uranium elements.

Here α and β are optical thickness for absorption and scattering of the uranium element and moderator respectively. When calculating the absorption cross section, the temperature of the neutron gas was defined in accordance with [3].
The uranium layer thickness and the shielding factor calculated by means of equation (1) are given in Table IV.

Since in all critical assemblies over 85% of fissions take place in the thermal region, we have not been essentially wrong, when we extended the calculated shielding factors to the total uranium blocking in the system.

As a rule the magnitude of the shielding factor cannot directly give the decrease of fuel load in homogenous systems, because

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of some effects occuring in thick elements (see e.g. [1]). In our case, however, these effects are small and the shielding factor itself is close to unity.

On multiplying the experimentally obtained values of the critical load and the shielding factor, we get values for G_{cr} for systems with homogenously arranged uranium.

Table IV.

Values of Shielding factor (f) for Assemblies with Lithium Hydride Moderators.

Assembly index	Uranium Layer Thickness	Shielding factor
HL - 1	113 mg/cm^2	0.844
HL - 2 and HL - 3	58 mg/cm^2	0.903
HL - 4 and HL - 5	26 mg/cm^2	0.948

3). The third correction eliminates aluminium present in the form of aluminium tubes of the core stacks (7 volume %) and spacing rings, indispensable for the porosity of the system. By this correction all the systems are brought to similar conditions as to the quantity of structural material (aluminium). The introduction of this correction is based on measurements of average core reactivity coefficients of aluminium and uranium. It comprises approximately~8% of the critical load.

4). Measures have been taken that the ratio of the core height to the equivalent core diameter should be close to unity. The corrections for the form factor, evaluated according to data quoted in [4] do not exceed 1%.

Table V and Fig. 1 present the critical parameters of the assemblies after all four corrections have been introduced. The introduction of corrections implies that the critical parameters correspond to those of homogenous cylindrical assemblies (where

the height and diameter are equal) with similar beryllium reflectors whose effective thickness is 9cm. The strong dependence of the critical parameters on the porosity of the system (or on the part of volume occupied by the moderator $\mathcal{E}_{LiH}$) should be noted. So should be the fact that the critical load decreases (when $\mathcal{E}_{LiH}$ = const.) with the decrease of H to U^{235} concentration ratios right to the ratio of 120, which is considerably lower than the optimal nuclear concentration ratio in a water moderated reactor.

The last circumstance is probably due to the decreasing of the thermal utilization factor in lithium hydride systems as compared with water moderated systems, because of the large capture cross section of lithium hydride (mainly, thanks to Li_6) in comparison to that of water.

T a b l e V.

Crit[illegible]cal Parameters of Assemblies with a Lithium hidride Moderator .

Parameters	HL-1	HL-2	HL-3	HL-4	HL-5
Composition of Assembly:					
$\rho_H/\rho_{U^{235}}$ including shielding factor	122	245	220	445	464
Volume percentage of lithium hydride (%)	34.6	36.0	43.4	43.4	57.7
Volume percentage of Uranium (%)	0.5	0.3	0.3	0.1	0.2
Critical Parameters without Corrections:					
Critical load (kg of U^{235})	4.[illegible]	5.95	4.32	4.52	4.06
Critical volume (l)	62.0	138.9	83.6	190	131.6
Corrections:x)					
1. Lattice distortion by control rods:					
a) change of load (kg of U-235)	-	-0.32	-0.22	-	-0.08
b) change of volume (l)	-	-7.4	-4.1	-	-2.6
2. Change of load due to shielding (kg of U-235)	-0.78	-0.54	-0.40	-0.24	-0.21
3. Change of load due to eliminating of aluminium (kg of U-235)	0.12	0.46	0.16	0.04	0.01
Critical Parameters with Corrections:					
Critical load (kg of U-235)	4.30	5.55	3.86	4.32	3.78
Critical volume (l)	62.0	131.5	79.5	190	129

x) The sign "+" indicates load or volume increase after introduction of correction.

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1.2. Critical Assemblies with Zirconium Hydride Moderator.

Assemblies with zirconium hydride moderator have a relatively hard neutron energy spectrum, being characterized by the nuclear concentration ratios of H to U^{235} 12.4 and 24.8. The assemblies with a zirconium hydride moderator are surrounded by a beryllium reflector 18cm thick (with the same volume percentage of beryllium and aluminium as the lithium hydride assemblies).

There is a steel layer more than 200mm thick, i.e. of practically "infinite" thickness, around the beryllium reflector.

Uranium oxide with steel shells have been used in these assemblies (see Table II). The composition of the two assemblies investigated is given in Table VI.

While determining the critical parameters, measures have been taken that the ratio of the core height to its equivalent diameter should be close to unity. This brings about a small critical number of core stacks (see Fig.2), which in turn requires a different technique for determination of critical parameters of the assemblies, since each core stack changes considerably the effective multiplication factor.

To find the critical parameters, several systems with equal core compositions but different in core height, that is with various amounts of elementary cells (fuel-moderator complects) in a core stack, have been assembled.

Some of the assemblies are subcritical, others insignificantly supercritical. The multiplication factor (K_{eff}) of the assemblies is determined by means of control rods, whose efficiency has been measured in these assemblies (beryllium blocks in an aluminium tube placed in the side beryllium reflector acting as control rods).

Having found K_{eff} as the function of the core height, the latter is determined by linear interpolation for $K_{eff}=1$ (see Fig.3).

In the same way the corresponding load of U-235 and the core volume are obtained.

With the help of interpolation lines the value $\frac{\Delta K}{K} / \frac{\Delta H}{H}$ (i.e. the relative worth of the core volume) can be determined.

This term characterizes the neutron leakage from the core and shows what changes the reactivity and fuel load will undergo on change of the height of the system.

Since the ratio of height to diameter of both systems is close to unity (i.e. the form factor introduces no significant corrections) the term $\frac{\Delta K}{K} / \frac{\Delta H}{H} \approx \frac{\Delta K}{K} / \frac{\Delta V}{V} \equiv \alpha$

The relative worth of the core volume of assemblies HZ-1 and HZ-2 turns out to be 30.2 β_{eff} and 31.0 β_{eff}, respectively (β_{eff} being the effective part of delayed neutrons).

After obtaining critical parameters the following corrections have been introduced:

1). Correction for reactor lattice distortions (namely, distortions of the reflector) by shut-down rod channels, introduced in the same manner as the analogical correction for assemblies with a lithium hydride moderator.

2). Corrections connected with the presence of steel (uranium elements shells) and aluminium in the reflector have been introduced with the aim of eliminating structural materials present in different quantities in the systems.

These corrections have been determined by means of experimentally measured steel and aluminium reactivity coefficients.

Table VII brings the corrected critical parameters of the assemblies.

The self-shielding effect of uranium elements due to their considerable thickness is also an important correction, influencing the critical load of the reactor.

To measure the shielding effect experiments have been made, where specific gamma-activities of "thick" uranium dioxide operating elements and "thin" ones composed of a uranyl uranate and teflon mixture (see Table II) placed close to the uranium elements have been compared. The shielding determined from the activity mea-

surements of the irradiated uranium elements by means of a scintillation device with a sodium iodide crystal (activated tallium) turned out to equal $f_{intern}(HZ-1)=0.73 \pm 0.02$ and $f_{intern}(HZ-2)=0.88 \pm 0.02$.

As mentioned above these magnitudes do not always give the decrease in critical load when we pass to a homogenous system. The more so that the uranium thickness in this case is considerable when compared to assemblies with lithium hydride moderators.

Table VI.

Core Composition of Assemblies with Zirconium Hydride Moderator.

Assembly index	Nucleus density x 10^{-20} 1/cm^3				
	H	Zr	U-235	Al	Steel[x]
HZ - 1	268	168	20.6	41	53
HZ - 2	268	168	10.3	51	27

[x] Average atomic weight of stainless steel in taken as 55.2.

Table VII.

Critical Parameters of Assemblies with a Zirconium Hydride Moderator (without shielding factor).

Parameters	HZ-1	HZ-2
Assembly composition		
$\rho_H / \rho_{U^{235}}$	12.4	24.8
Volume percentage of Zr Hydride (%)	51.0	51.0
Volume percentage of U (%)	4.9	2.4
Critical parameters without corrections		
a) critical load (kg of U-235)	8.88	5.83
b) critical volume (l)	11.1	14.4
Corrections[x]		
1. Reflector lattice distortion by emergency channels.		
a) ΔG_{cr} (kg of U-235)	-0.04	-0.05
b) ΔV_{cr} (l)	-0.05	-0.13
2. Presence of Steel in Core and Reflector		
a) ΔG_{cr} (kg of U-235)	-0.71	-0.50
b) ΔV_{cr} (l)	-0.89	-1.22
3. Presence of Aluminium in Core and Reflector		
a) ΔG_{cr} (kg of U-235)	+0.34	+0.20
b) ΔV_{cr} (l)	+0.42	+0.49
Critical Parameters corrected		
a) critical load (kg of U-235)	8.47	5.48
b) critical volume (l)	10.6	13.5

[x] The sign "+" indicates the increase of critical load or volume after introduction of correction.

NEUTRON SPECTRUM ENERGY MEASUREMENTS IN ASSEMBLIES WITH A ZIRCONIUM HYDRIDE MODERATOR.

Experimental study of neutron spectra in multiplying media at different moderator-fuel ratios is of considerable importance both to the moderation and diffusion theory and to reactor physics.

Comparison of calculated and experimental results is of great help in many respects: we may improve models and methods of calculation, correct systems of constants for multigroup calculation and have a deeper insight into the physics of processes going on in a nuclear reactor.

As a rule the most interesting energy region is the thermalized neutron region, where various effects of chemical bonds of moderator atoms can be observed in the neutron spectrum behaviour.

In nuclear reactors with hydrogenous moderators a comparatively soft neutron spectrum is obtained, even with small nuclear concentration of hydrogen and fissile material. Therefore the great interest for the formation of the neutron spectrum of various hardness in reactors containing a zirconium hydride moderator is quite justified.

A characteristic feature of zirconium hydride as moderator is the fact that the bond between the proton in the lattice and the zirconium atoms is rather rigid, the vibration energy being 0.13ev. That is why the neutron, when moderated, loses its energy by 0.13ev portions and why the energy loss of a neutron with the original energy less than 0.13ev is being impeded and is rather ineffective.

In consequence of this behaviour of the neutron in zirconium hydride there is a considerable deviation in the neutron density distribution from the Maxwell distribution at small absorption amounts per hydrogen atom.

A mechanical selector operating with the critical assembly can be successfully used to investigate neutron spectra of highly enriched systems with a broad energy range. The application of a selector technique as part of a critical assembly has a number of ad-

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vantages when compared to a subcritical assembly in the column of a powerful reactor. It is very convenient that information on the neutron spectrum is obtained together with other experimental material, that the experiments is conducted in conditions close to the real ones, that there is no need of an external neutron source, etc. The fast chopper of the PF-4 physical assembly enables us to measure neutron spectra with a broad neutron energy range. Fig. 4 gives the experimental set-up on neutron spectra measurements of the critical assembly under investigation.

A beam of neutrons is passed from the investigated part of the assembly by means of a rectangular channel through a slit collimator to a mechanical chopper. The cross section of the channel close to the luminous surface is 50mm x 50mm. The rotor of the chopper is a hetinax disc 240mm in diameter in a casing of stainless steel. The four slits of the chopper have a spindle-shaped form (a 2mm slit width at the input and output and 4mm in the central part of the rotor). There are two slit systems in the rotor that are set under an angle of 90^0 to each other. This last condition makes it possible to get four neutron impulses per one revolution of the rotor, the recycling condition being fullfilled for the flight base up to 11m. The rotor is designed for a rotation speed up to 12000rpm, with a maximum flight base of the selector of 9m. On the rotor surface at certain intervals from the slits there are 0.1 mm grooves containing magnetic material. When rotating the magnetic reading device produce short electric pulses that are used for starting the time analyser until a neutron impulse enabling the background counting measurements appears. The background counting is measured as a function of the angle of turning of the chopper. This can prove important for a correct estimate of the background when a sufficiently, intensive, hard neutron component is present in the beam.

To reach a satisfactory statistical exactness in spectrum measuring a comparatively high power level of the critical assembly is required. This is connected with fuel activation. An increased

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activity of the core stacks may sometimes hamper the setting up of other experiments. The application of sufficiently effective neutron detector and the increase of the transmission of the selector lead to a decrease of the activation effect of the core stacks.

In the assembly investigated an ionizing chamber filled with He^3 at a pressure of 18 atm, similar to the one described in [5] serves as neutron detector.

The spherical casing of the chamber (100mm in diameter with a well thickness of 1mm) is made of steel, the inner electrode having a 5mm diameter.

The working voltage ~2.5kv. Amplified signals went after discrimination into a 256 channel time analyser. Thanks to the shielding and collimator system of the selector a rather good ratio of the measured effect to the background was obtained. By means of this mechanical selector neutron spectrum measurements of the two assemblies with zirconium hydride moderators have been accomplished.

In both assemblies the beam comes from the central region, the luminous surface (50mm x 50mm) containing six elementary cells of core stacks. This brings about the averaging of the neutron spectra per cell. The axis of the beam channel coincides with the centre of the core.

Fig.5 includes the experimental curves of the neutron flux vs. energy, the curve reference being chosen arbitraril. When the spectrum of the device was being treated a number of correction was made: corrections for the perviousness function, for the detector effectiveness, the resolution, the distortion of the spectrum by absorption in air and in the detector wall, the neutron flux scalar gradient and for the flux perturbation by the beam output cavity.

The neutron scattering effect in air that took place in the part of the tube close to the luminous surface was calculated separately. 876

The selector resolution amounted to $\sim 15\frac{msec}{m}$. Additional measurements of the neutron spectrum at decreased rotation speed of the rotor was accomplished in assembly HZ-2 with the view of a more detailed insight into the flux flow in the low-energy region.

The significant statistical error of experimental results is to be explained by the insignificant effect and background difference in this neutron energy region.

From the given flux distributions it is to be concluded that neutron density cannot be described in terms of the Maxwell distribution.

The comparatively narrow maximum flux close to the energy region of 0.13ev is significant. The high absorption per hydrogen atom (~ 50b in HZ-1 and ~25b in HZ-2[x)]) gives rise to a strong display of the effect of chemical bonds. The comparatively fast decrease of the neutron flux with energies lower than 0.10ev is another characteristic feature of the results quoted.

It should be noted that the experimentally measured values of the subcadmium and supercadmium fissions of U^{235} ($CdR_{U-235}-1$) are relatively high - 0.8 and 1.8 for assemblies HZ-1 and HZ-2 respectively.

Nevertheless as mentioned before neutron fluxes decrease fast with energy at $\leqslant 0.1$ev. It follows that the high value of ($CdR_{U-235}-1$) does not indicate large thermal neutron fluxes as it is usually assumed.

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[x)] The absorption in given per atom at V_n=2200m/sec.

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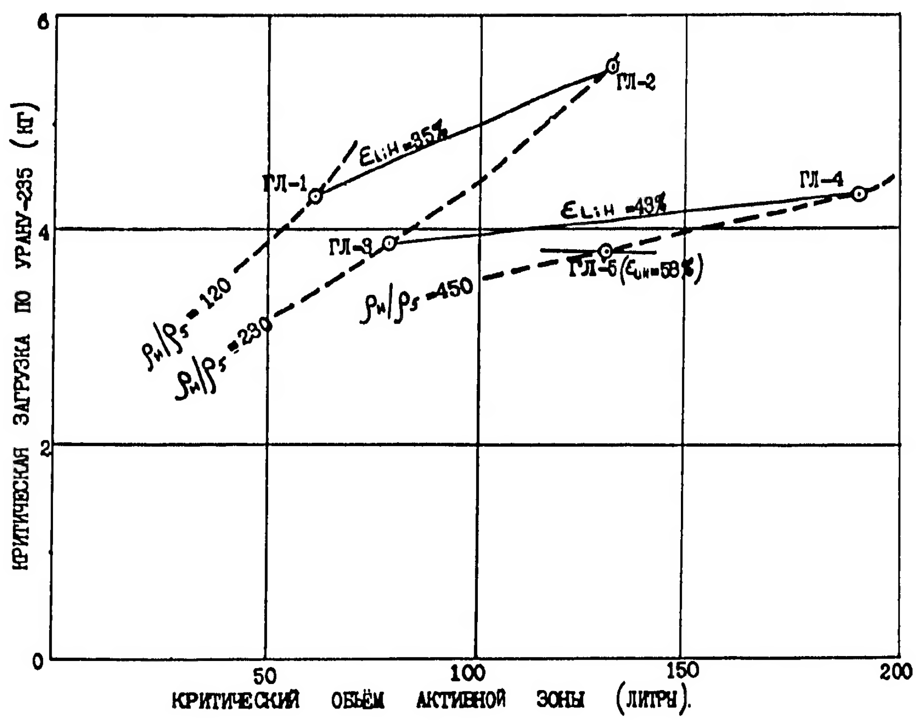

Fig. 1. Critical Parameters of Assemblies with Lithium Hydride Moderators.

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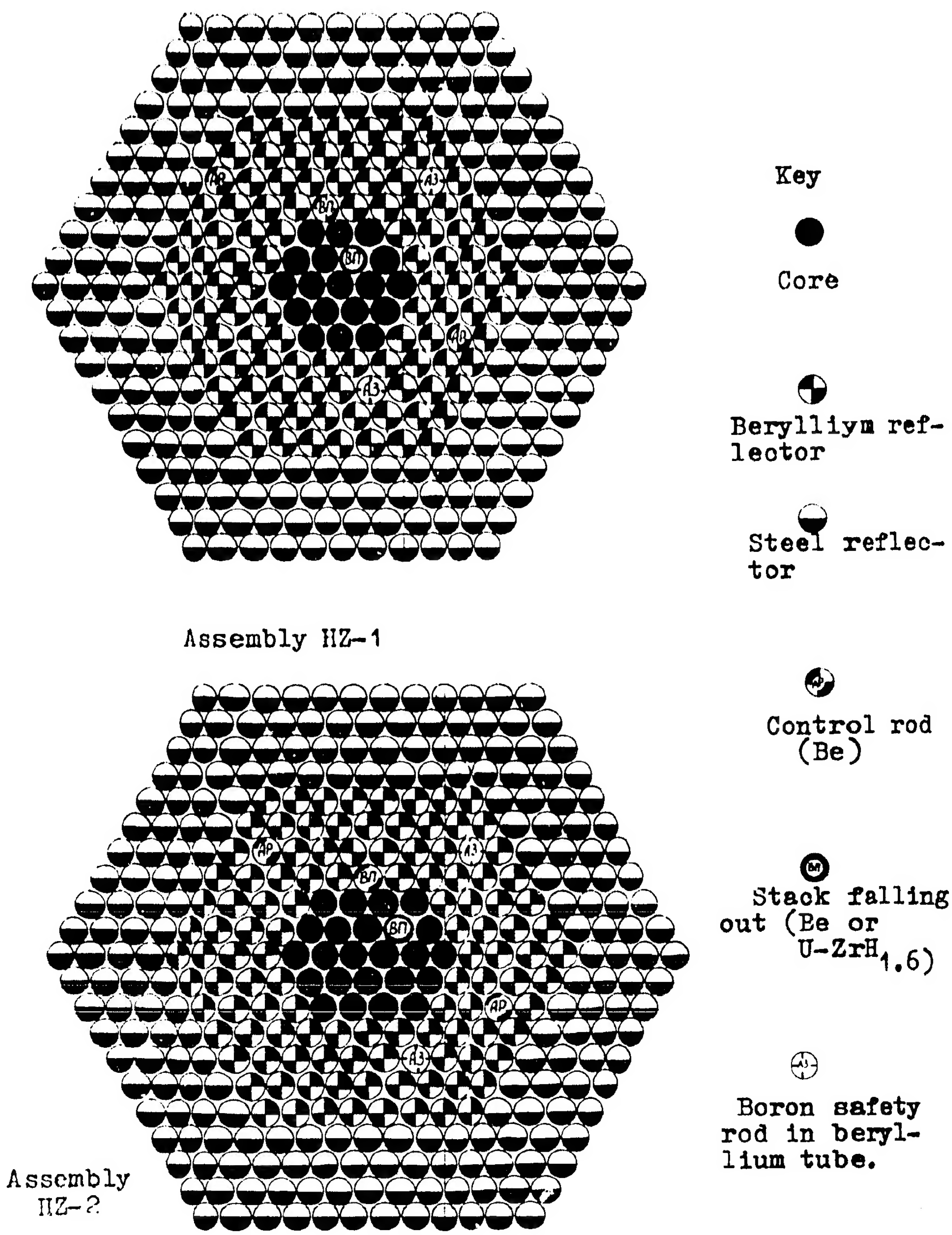

Fig. 2. Arrangement of Core Stacks Assemblies with $ZrH_{I.6}$ Moderator.

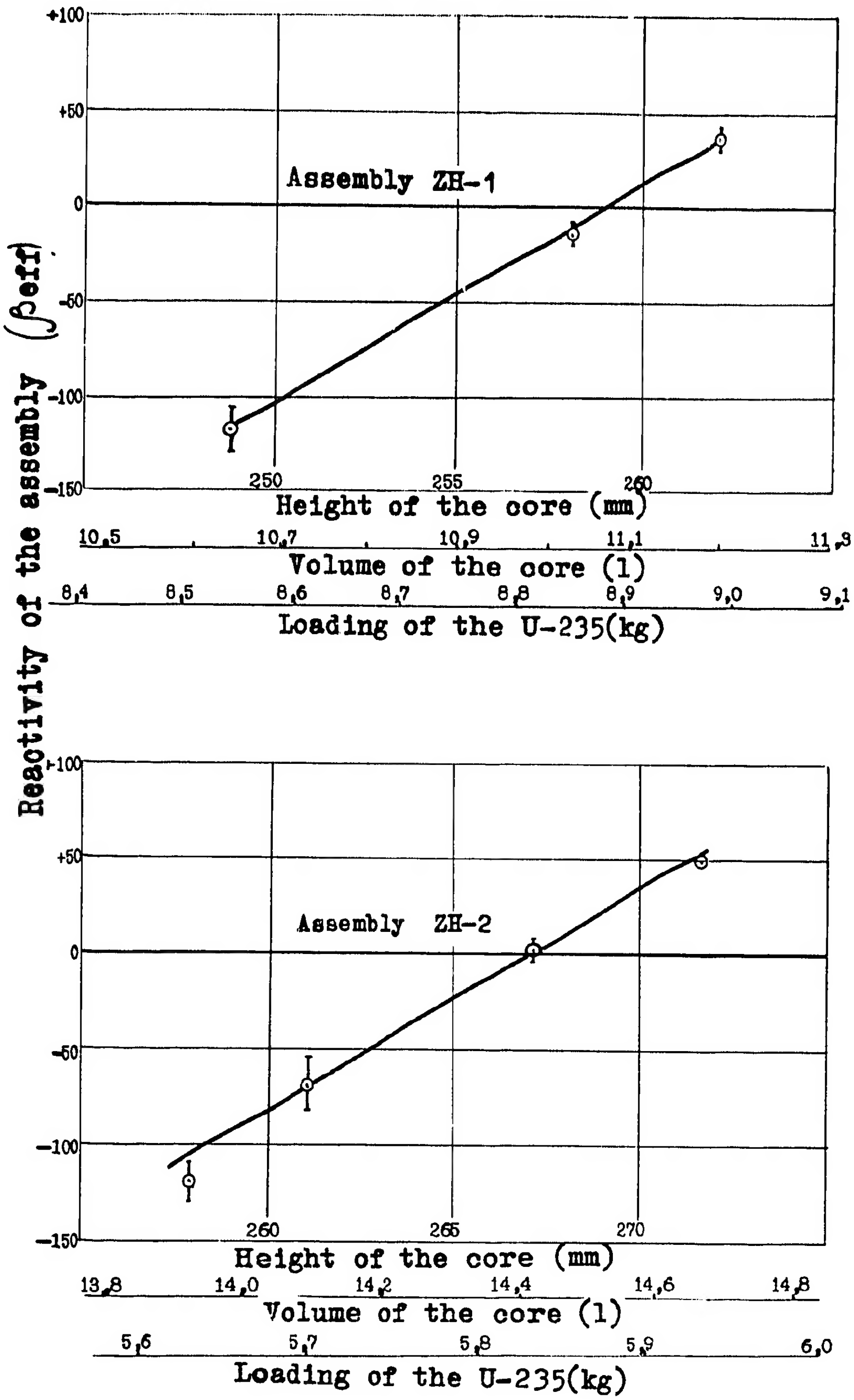

Fig. 3. Interpolation of Assembly Parameters for Critical Values.

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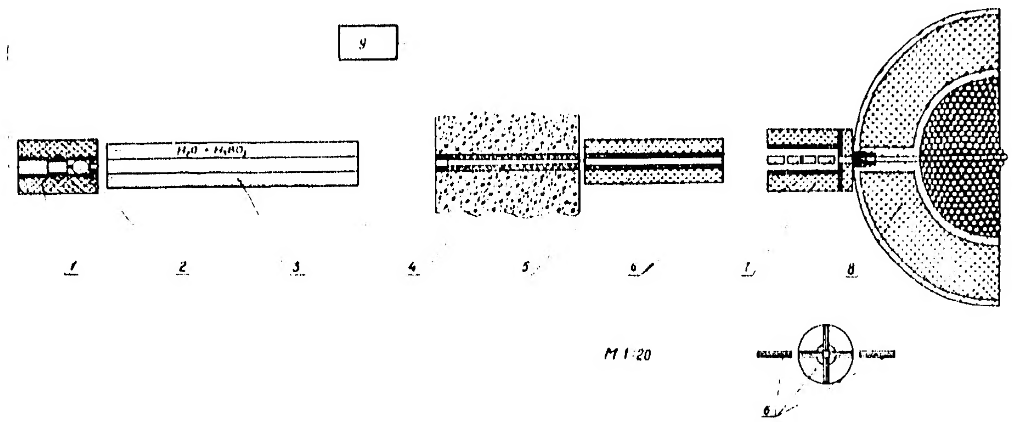

Fig.4 Geometry of Experiments on Neutron Spectra Measurements
1-Reactor hielding; 2-Detector(He^3 chamber);3,4,5,Collimators; 6-Rotor and Slit Collimators; 7-Chopper Shielding; 8-Biological Shielding of Assembly; 9-Time Analiser.

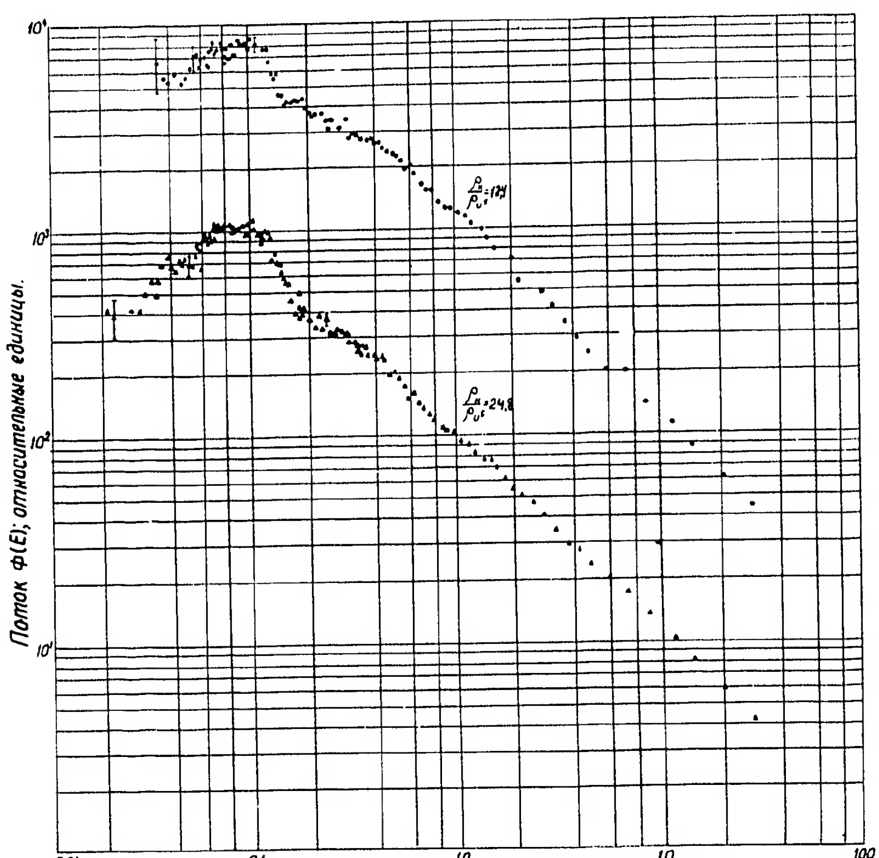

Fig.5. Energy Distribution of Neutron Flux for Critical Assemblies with a Zirconium Hydride Moderators.

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